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THE DEVELOPMENT OF QUANTITATIVE NDI FOR RETIREMENT-FOR-CAUSE.(U)

FEB 79 J M HYZAK, J E ALLISON, W H REIMANN

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THE DEVELOPMENT OF QUANTITATIVE NDI FOR RETIREMENT-FOR-CAUSE

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TECHNICAL REPORT AFML-TR-78-198
Final Report for Period September 1975 to June 1976

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To investigate the viability of quantifying NDI signals, relationships between eddy current signals and flaw dimensions were examined. The prime emphasis of this report is exploring these relationships and the difficulties encountered in establishing them. A fracture mechanics/NDI-based disk rejection over

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criteria, retirement-for-cause, which required quantitative NDI, is also described. The case of radially cracked bolt holes in a turbine disk inspected by a semiautomatic eddy current technique is used to illustrate the procedures.

Monotonically increasing relationships, primarily logrithmic in nature, were observed between signal characteristics and the dimensions of EDM notches which were used to model actual cracks. Sensitivity level and eddy current system choice were observed to significantly affect the eddy current/flaw dimension relationships.

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FOREWORD

This report describes a joint inhouse effort by personnel of the Air Force Materials Laboratory and the Air Force Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. Dr. W. H. Reimann and Capt. J. M. Hyzak are members of the Metals Behavior Branch (LLN), Metals and Ceramics Division, Air Force Materials Laboratory. At the time of this work, Capt. J. E. Allison was a member of the Structural Integrity Branch (FBE), Structural Mechanics Division, Air Force Flight Dynamics Laboratory. Presently Mr. Allison is at Carnegie-Mellon University, Pittsburgh, Pennsylvania.

The work reported herein was performed during the period September 1975 to June 1976 under AFML Project 2307P102, "Engine Life Prediction", and AFFDL Project 2307N101, "Research in Structural Integrity". This research was presented at the American Society for Metals and American Society for Non-Destructive Testing 4th Annual Forum on "Prevention of Fracture Through Non-Destructive Inspection", 12 June 1976, Tarpon Springs, Florida.

The authors would like to express their appreciation to Mr. Grover Hardy of The Air Force Materials Laboratory (MXA), and Messers. Ron Selner and Harold Kamm of Universal Technology Incorporated who performed the eddy current inspections. The authors are also thankful to Mr. E. Frick of 4950th Test Wing (AMFED), Wright-Patterson Air Force Base, for fabricating the EDM slots in the turbine disks.

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INTRODUCTION

The design of recent jet engines entering USAF service has emphasized increased performance and higher thrust/weight ratios, resulting in higher stresses on rotating components. This in turn has led to the introduction of larger numbers of finite life components. For example, most rotating disks tend to have relatively short low cycle fatigue (LCF) lives. Since these disks have rapidly increased in cost due to design complexities and the use of advanced materials and processing techniques, the cost of maintaining these advanced engines has also escalated dramatically in the same time period. It is important then that ways be sought to optimize the useful service lives of these components.

In this report an alternate approach, referred to as Retirement-for-Cause (RFC), is described. It is believed that this technique, which is based on a fracture mechanics analysis of the crack propagation phase, can in fact optimize the service life and thereby minimize maintenance costs.

It will also be shown that the successful application of Retirement-for-Cause is highly dependent on nondestructive inspection (NDI) capabilities. Furthermore, this NDI requirement is more quantitative than has generally been considered in the past since it becomes necessary not only to detect the defect (crack) but also to describe it in considerable detail and with a high degree of reliability. While the quantitative aspects of NDI have only

recently begun to be explored in detail, data will be presented that indicates that the necessary degree of quantification appears to be possible (1,2).

SECTION II

RETIREMENT-FOR-CAUSE AND NDI REQUIREMENTS

Traditionally , components whose life limit is controlled by fatigue have been designed to a crack initiation criterion. The component is considered to have failed as soon as a crack of some finite size, e.g., .031" (.8mm) has formed and the part is removed from service (3). No attempt is made to utilize the remaining life associated with the crack propagation phase.

From a safety standpoint, this approach has been generally very successful since it contains a built-in safety factor associated with crack propagation. However, for real materials and for real design situations, lifetimes based on time to crack initiation tend to be extremely conservative. This may be seen by reference to Fig. 1, which illustrates the crack initiation behavior of Inconel 718, a typical nickel-based superalloy, at $1000^{\circ}F$. Because of

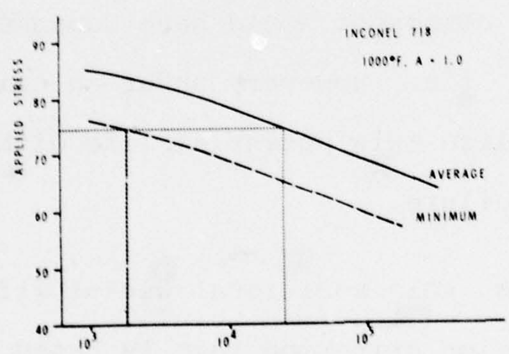

Fig. 1 S/N Diagram for Turbine Disk Alloy, Applied Stress vs Cycles to Crack Initiation

the statistical nature of the crack initiation process, there is a significant scatter associated with the number of cycles to initiate a crack at some given stress level. For design purposes this problem of materials scatter is usually eliminated by degrading the S/N curve to a level where the probability of failure, i.e., crack initiation, becomes low enough to ensure structural integrity of the component. For critical components such as engine disks, this probability is usually set at 0.1%. Figure 1 shows a design allowable curve based on this probability of initiation. In service a fatigue limited component would be used for the number of cycles permitted by this design curve and then all such components would be retired. Theoretically, at this design life only one component of a population of 1000 would have actually initiated a crack and the remaining 999 components would have some undefined useful life remaining. Reference to Fig. 1 shows that in the case illustrated the difference between the number of cycles to reach the design curve and the mean are significantly different and that at the design limit an average component would have consumed 10% or less of its potential useful life. However, under an initiation criterion there is no way to utilize this potential life without accepting a higher probability of failure.

Nevertheless, this additional useful life can be utilized by adopting a rejection criterion that is based on crack propagation rather than initiation (3). The development of fracture mechanics concepts over the last several years has permitted the degree of predictability for crack propagation necessary to implement such an approach.

Figure 2 shows the basic retirement-for-cause concept. For a given component, the number of cycles, N_c, required to propagate a crack from an initial size A_o to critical size A_c can be calculated. This number of cycles, N_c, then becomes the upper bound for a cracked component to remain in service. An inspection interval is then established at some fraction of N_c designated N_I. It can be seen that over this interval of time no component containing a crack equal to or smaller than A_o could fail catastrophically.

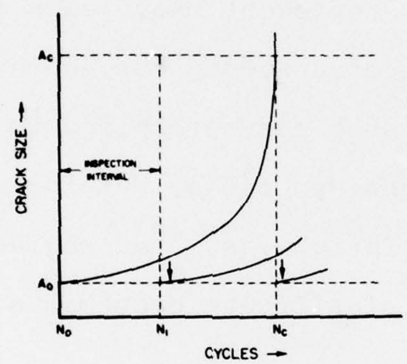

Fig. 2 Crack Growth/NDI Relationship for Retirement-for-Cause

In operation, components would be inspected at the end of the design life, and only those components containing cracks equal to or greater than A_o would be retired. All others would be returned to service. After an additional N_I cycles those components would again be inspected and again all cracks larger than A_o rejected and the remainder returned to service. In this way the crack propagation residual life is continually rezeroed to A_o. By following this approach, components are only rejected for cause

(cracks) and the remainder are allowed to operate for the maximum useable time.

It is clear that not all fatigue-limited components may be handled in this way, and that each component must be evaluated individually to determine the economic feasibility. The inspection interval N_I (Fig. 2) must be such that it does not place undue constraints on the operation of the component or that the cost of the necessary tear down and inspection does not negate the advantages of the life extension gained. One thousand cycles of crack propagation may represent many years of service for one component and a fraction of a second for another. It seems unlikely that retirement-for-cause can be applied to components limited by high cycle fatigue considerations, but for many high cost components limited by low cycle fatigue, such as engine disks, this approach does appear to offer significant economic advantages.

It is also clear that in applying retirement-for-cause, nondestructive inspection becomes a critical factor. The value of A_o in Fig. 2 determines the residual life of the component and is limited by the resolution and reliability of the inspection system employed. In many cases the decision as to whether or not retirement-for-cause can be applied to a component will be predicated upon the ability of available NDI approaches to detect A_o with sufficient sensitivity and reliability. Because the RFC analysis includes an indepth stress analysis, a component's defect on critical locations can be accurately predicted. For this reason, NDI techniques can be selected and refined for a particular area

rather than attempting to develop a technique for characterizing the quality of an entire component. This inherently increases the sensitivity of the system to a level where RFC can be utilized. Preliminary crack growth analyses indicate that the detection and elimination of cracks larger than .030-.050" surface length (2c) would provide adequate residual life for the application of RFC to many older disk designs, and this was the crack size of primary interest in the present study. However, it is also recognized that in some of the more advanced designs, using higher strength, lower toughness material, the acceptable level for A_o may be much smaller.

A program of which this research is a part, is looking at the possibility of applying a RFC rejection criterion to a particular turbine disk that is life limited in the bolt hole region due to LCF cracking. A semiautomatic eddy current technique which has undergone extensive development for the inspection of fastener holes in airframes is being reviewed for this engine component application (4). Since cracking around both cooling and bolt holes is becoming an increasing problem, the development of such advanced eddy current techniques is desirable. A particular area of eddy current technology that deserves considerable investigation is that of signal interpretation. In particular, it seems reasonable to suggest that there are various relationships that can be established between signal characteristics and actual flaw dimensions (5). If such correlations could be determined, the information would significantly impact the implementation of reject

criteria such as retirement-for-cause. Inspection techniques could be altered from the basic "go no-go" type to systems which provide opportunity to more easily establish rational reject limits. Another application of such a system is that it would provide an opportunity to accurately determine the shape of a flaw during growth. Both crack growth lives and critical flaw sizes are very sensitive to the aspect ratio of crack, that is, the ratio of the surface length of the crack to the maximum depth. In a RFC analysis for a particular turbine disk, the crack growth lives varied by a factor of 2.5 for the range of flaw aspect ratio, 0.25-0.5. The following discussions will describe research aimed at examining the feasibility of establishing quantitative relationships between eddy current inspection signals and actual crack.

SECTION III

SIGNAL QUANTIFICATION

1. APPROACH

To develop the correlation between signal characteristics and flaw size, the approach originally decided upon was to nondestructively inspect retired, high time disks using the eddy current technique and subsequently to destructively determine the size of detected flaws. Specifically, the cracked areas were to be cut from the disk, oxidized at 1400°F to decorate any fatigue cracks open to the surface, and finally broken open at cryogenic temperatures to reveal the fatigued areas (Fig. 3). The procedure was quite successful for what are considered large cracks (greater than .100" surface length).

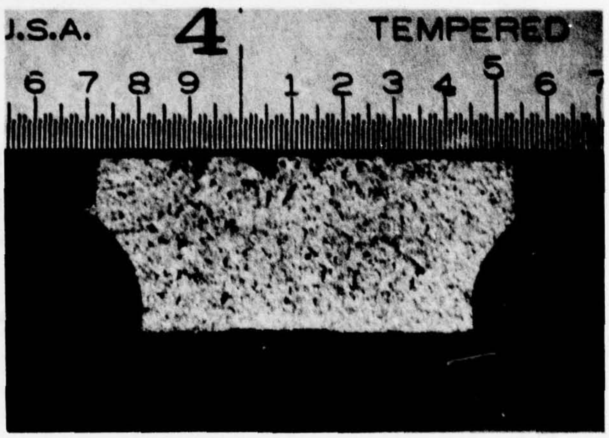

Fig. 3 Service Induced Crack Oxidized to Reveal Fatigued Area (Divisions 0.10 inch)

However, for smaller cracks there were several problems that were encountered. In particular, fatigue cracks in the specific disk material studied, Incoloy 901, generally initiated in several places in the bolt hole radius and the initiation sites were frequently noncoplanar as is illustrated using high resolution dye penetrant (Fig. 4). Thus it was impossible to reveal the entire crack using the above procedure. The only alternative method of documenting the total flaw size was considered to be metallographic sectioning. The amount of effort involved in obtaining sufficient data to establish quantitative relationships, however, seemed prohibitive without further evidence to support the feasibility of the concept.

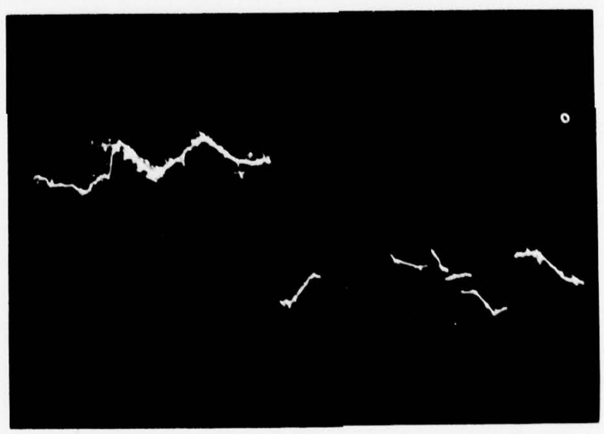

Fig. 4 Penetrant Enhanced Observation of Noncoplanar and Multiple Cracking

As an initial effort to examine the possibilities of signal quantification and to circumvent the problems with crack size documentation, it was decided to utilize manufactured notches in the study. Flaws were electron discharge machined (EDM) in retired disks that were free of any detectable fatigue cracks. Twenty notches were machined with varying aspects ratios in the range of size .011-.282" deep by .030-.755" in surface length (Table 1). Width of the notches was from .005 to .007". Although, potentially, the major value of signal quantification lies in the small crack range, it was decided to extend the study to the larger flaws in order to better analyze any physical relationship that might control the correlation between eddy current signals and flaw dimensions.

Notches were machined in two basic shapes, rectangular and semielliptical. Dimensions were determined by making silicon rubber impressions of each slot and measuring the lengths on an optical comparator (Fig. 5). Photographs were taken of each impression and the area of each notch was measured.

2. EQUIPMENT AND EXPERIMENTAL PROCEDURES

Two different eddy current systems were used for this research. System A, shown in Fig. 6, consisted of an Automation Industries Model EM3300 eddy current instrument, Tektronix oscilloscope and Mosely X-Y recorder. The EM3300 vertical output was AC coupled to the oscilloscope so that constant of DC signals were not recorded. The oscilloscope provided an output proportional to its vertical

TABLE 1

EDM NOTCH DIMENSIONS

Semielliptical

Length (in)	Depth (in)
.037	.011
.047	.019
.076	.027
.118	.044
.236	.066
.300	.097
.461	.138
.603	.208
.671	.282

Rectangular

Length (in)	Depth (in)
.030	.013
.030	.015
.051	.015
.062	.015
.081	.029
.111	.036
.209	.060
.303	.100
.485	.127
.755	.182

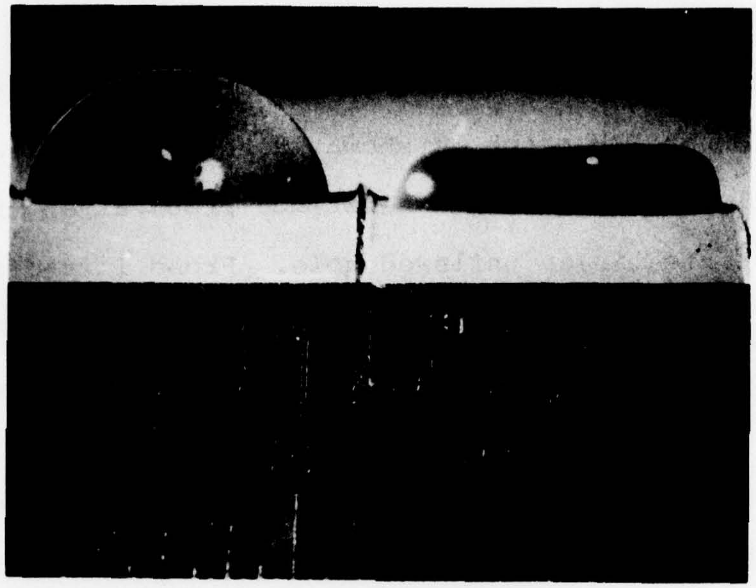

Fig. 5 Silicon Rubber Replicas of EDM Notches (Divisions 1/32 inch)

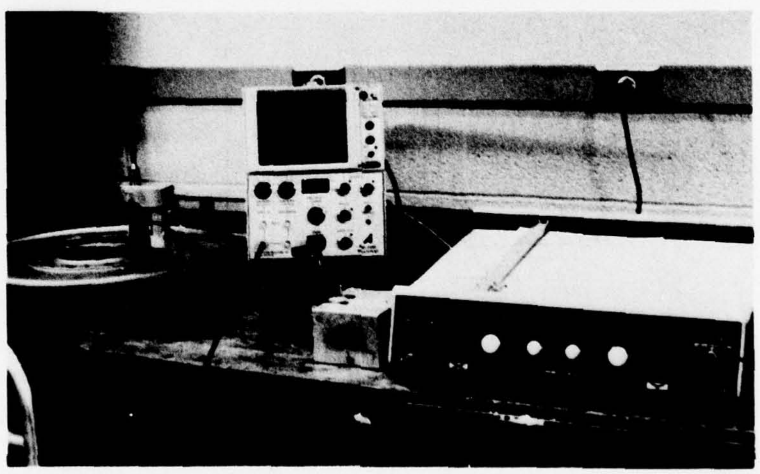

Fig. 6 Eddy Current System A and Semiautomatic Rotating Scanner in Place on Turbine Disk

signal which was recorded on the X-Y recorder. A typical signal recording from an EDM notch is shown in Fig. 7. The test coil was electronically balanced with a reference probe after the test probe was inserted in an unflawed hole. Probe lift-off correction was made by applying finger pressure to the probe and adjusting the impedance plane phase control such that any indication due to lift-off was in the horizontal direction only, thus the only vertical signals recorded were those due to conductivity changes such as those produced by passing the coil over a discontinuity. Experimentation was conducted at two sensitivities (gain settings). The excitation frequency was fixed at 500 kHz.

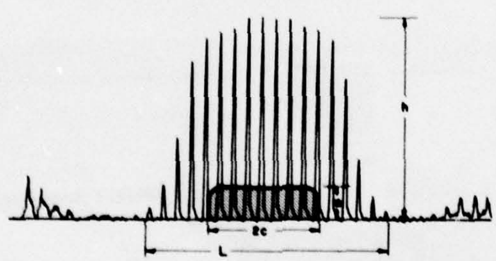

Fig. 7 Typical Eddy Current Signal from EDM Notch (Superimposed)

The Gulton Industries Model ND2 was the basis of System B. This system used the Magnaflux ED520 eddy current unit which outputs its signal (AC coupled) to a Techni-rite strip chart recorder. The test coil was balanced electronically and lift-off corrections were accomplished by adjusting the coil excitation frequency. The normal operating frequency was 100-200 kHz. Various sensitivity levels were employed with system B by adjusting the strip chart recorder gain settings. Signals from system A and B were recorded without electronic filtering, other than the high pass AC coupling.

A semiautomatic scanner (Fig. 6) was used to rotate the eddy current probe in a spiral manner through the disk bolt holes. The probe extended axially .025" with each revolution. Scan speeds were held constant at one revolution per second. An absolute eddy current coil embedded in a .625" diameter **Teflon** probe was used for all recordings.

Two scans were made for each bolt hole inspection with an initial coil location for each 180° apart. This effectively increased the resolution of each scan to approximately .0125" per revolution. All recordings were made with the probe extending into the bolt hole. Flaw signals were recorded on hard copy and then were digitized using a Hewlett Packard 9820, desk top calculation/digitizer. In addition to measuring the maximum height, h, and the number of vertical deflections, L, the calculator numerically integrated the digitized signal to obtain the signal area A_{EC}.

3. RESULTS AND DISCUSSION

The experiment was designed to investigate how three basic characteristics of the eddy current signal varied with specific changes in flaw shape using two eddy current systems. The relationships of interest (Fig. 7) were the variation of eddy current signal area, A_{EC}, with notch surface area, A_N; changes in eddy current maximum signal height, h, with notch depth a; and the number of vertical eddy current signal deflections, L, with notch surface length, 2C.

The experimental results are shown in Figs. 8-12 for eddy current system A. The variation of maximum signal height, h, is plotted versus notch depth, a, in Fig. 8 for both

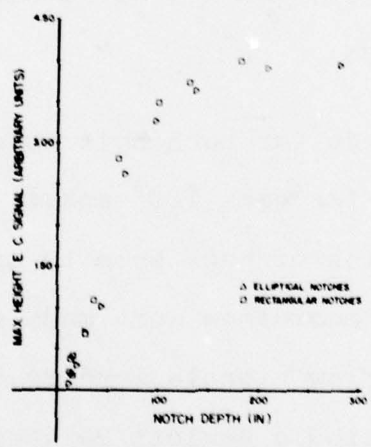

Fig. 8 System A: h vs a for Two Notch Geometries

shapes of notches. These appeared to be a logarithmic increase in the maximum height of the signal as the notch depth was increased with minimal effect due to notch geometry. This logarithmic behavior was attributed to the well known skin effect phenomenon which causes the eddy currents to be concentrated near the surface adjacent to the coil and to decrease exponentially with depth (5).

Additional data were plotted in Fig. 9 for the notch depth/maximum peak height relationship. In this case, the data represented readings for the elliptical notches at two sensitivities using system A. The sensitivity level was described by the normalizing factor (A/A*) where A is the eddy current signal area for the particular sensitivity setting and

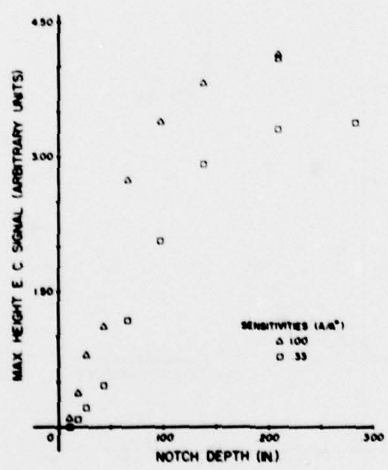

Fig. 9 System A: h vs a for Two Sensitivity Levels

A* is the signal area for the maximum sensitivity used in these experiments. As (A/A*) increased, the sensitivity increased. This figure illustrates that at lower sensitivity levels the same logarithmic trend was apparent and the saturation level was not single valued.

A montonically increasing relationship was also observed when eddy current vertical deflections were plotted versus notch surface length (Fig. 10). In this case, however, there appeared to be a significant geometry effect. It was believed that the variance in response can be attributed to the differences in aspect ratio between the two sets of notches. It was also observed that for small notches a large number of vertical peaks were recorded. This is demonstrated in Fig. 10 by an

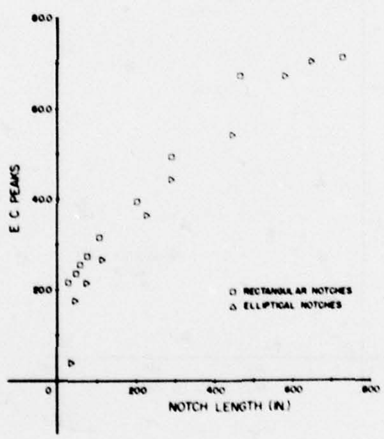

Fig. 10 System A: L vs 2c for Two Notch Geometries

apparent nonzero ordinal intercept for the rectangular notches and was due to the large area or aperture over which the probe senses. The actual sensing diameter of the probe was estimated to be 0.22-0.24" (5.5-6.0mm) for this particular sensitivity level. This large sensing diameter also caused the number of vertical indications, L, to saturate as the notch surfaces length neared the edge of the bolt hole. Subtracting the aperture diameter, 0.23" (6mm), from the specimen thickness, 0.83" (21mm), one would expect the number of vertical indications, L, to increase linearly with surface length in the crack range 0L2CL0.6" (15.mm). This appeared to be approximately the case in this investigation.

Plotting similar data for two different sensitivity levels, Fig. 11 illustrates the slight shift in the relationship as the

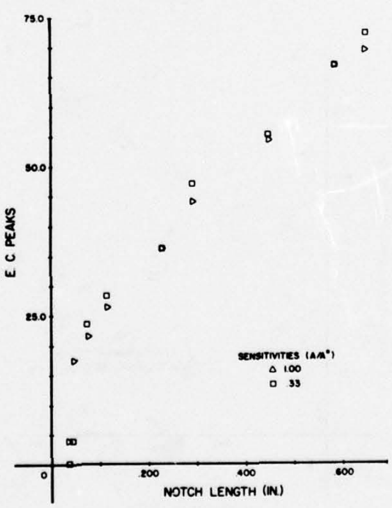

Fig. 11 System A: L vs 2c for Two Sensitivity Levels

sensitivity was altered. Of more interest, however, were the nonlinear points in the lower crack range (.037"-.047" surface length). Based on the majority of data for this relationship, it is believed that these points deviated from linearity because of the lack of system sensitivity in this crack range. This lack of sensitivity was due to a low signal to noise ratio for these data points. It can be seen that increasing the sensitivity from (A/A*) of .33 to 1.0 reduced the scatter.

The relationship between the area of the eddy current signal, A_{EC}, and the surface area of the notch A_N is shown in Fig. 12. Here, again there was a monotonically increasing function which appeared to be independent of notch geometry. The relationship reached a saturation value which was due to the exponential decrease in current density with depth of penetration.

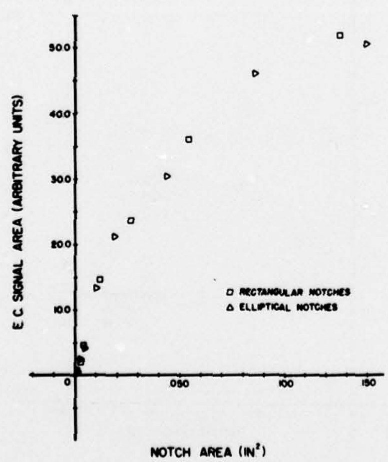

Fig. 12 System A: A_{EC} vs A_N for Two Notch Geometries

The experimental results utilizing eddy current System B are presented in Figs. 13-15. These data represent a range of different sensitivity levels, but only for the rectangular notches. In general, the results for System B follow the same trends as those reported for System A. The eddy current signal height, h, versus notch depth, a, relationship for varying sensitivity levels is presented in Fig. 13. Saturation was much more apparent for these results when compared with those results for System A (Fig. 9). This difference was attributed mainly to recorder saturation, and, thus, the logarithmic relationships which would be expected was truncated. One can also see in Fig. 13 that as the sensitivity of the system was increased, upper range saturation became more of a problem. In addition, there appeared to be a lower bound saturation for System B; no explanation of this behavior is apparent.

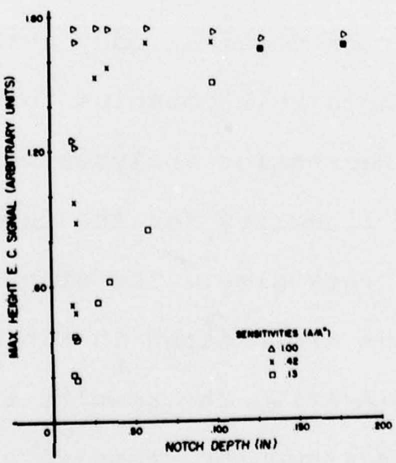

Fig. 13 System B: h vs a for Three Sensitivity Levels

Eddy current signal area is plotted versus notch area in Fig. 14 for several sensitivity settings. As with System A, the relationships were relatively well behaved monotonically increasing functions. Sensitivity of the eddy current system, again, significantly affected the signal.

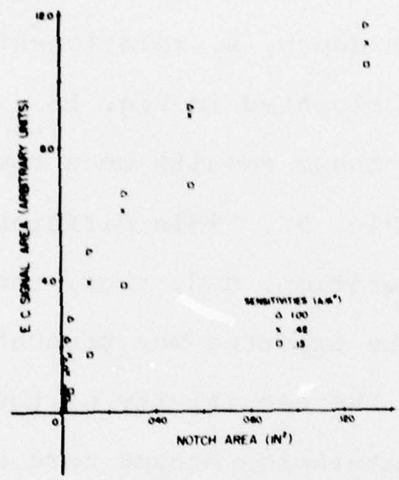

Fig. 14 System B: A_{EC} vs A_N for Three Sensitivity Levels

Finally, the number of vertical eddy current indications versus notch surface length relationships for system B are presented in Fig. 15. Regression analyses were performed to determine the degree of linearity for the three sensitivities over various ranges of crack size. The standard error of these best fits relations are plotted in Fig. 16 versus the sensitivity parameter, (A/A*). The results indicated that for the smaller notch length range the standard error decreased slightly as the sensitivity increased. In the larger notch range, however, the relationships deviated significantly from

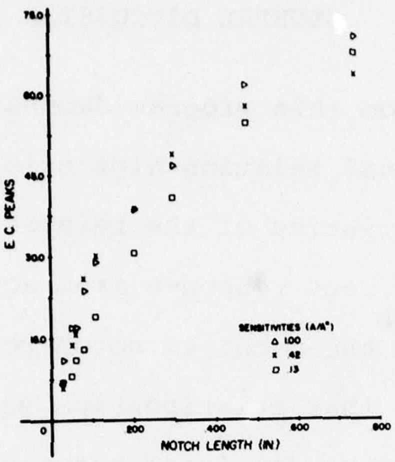

Fig. 15 System B: L vs 2c for Three Sensitivity Levels

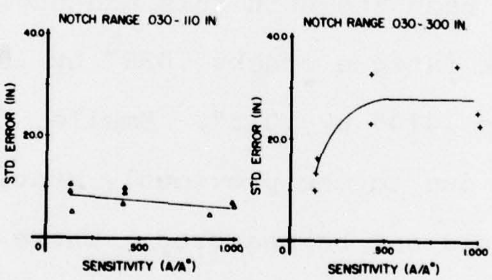

Fig. 16 System B: Standard Error from Linear Regression Fit Over Two Notch Size Ranges vs Sensitivity Levels

linearity as the sensitivity was increased. This can be attributed to the saturation effect observed as probe approaches the edge of the bolt hole.

SECTION IV

GENERAL DISCUSSION

The findings from this program demonstrated that relatively well behaved functional relationships exist between notch size and various characteristics of the related eddy current signal. Although the eddy current response from actual fatigue cracks may well differ from the machined notch response, it seems reasonable to assume that relationships similar to those reported herein could be developed between eddy current signals and actual fatigue cracks.

It has been demonstrated that the eddy current inspection technique is sensitive enough to readily detect small flaws. This technique has been shown in this and preliminary work to successfully detect fatigue cracks .030" by .040" and EDM notches as small as .010" by .015". Smaller fatigue cracks were detected; but due to the previously mentioned difficulties the actual size could not be measured. These results support the conclusion that RFC is technically feasible from an NDI standpoint for those older design disks which have demonstrated adequate crack propagation time from this size of detectable flaw.

This research has indicated particular variables that may be important in defining signal/flaw dimension relationships for fatigue cracks. It has been shown that the sensitivity range of the system can significantly affect the type of signal

response. In particular, the results suggest that there is an optimum sensitivity for a particular instrument and range of crack sizes. The sensitivity has been defined by the parameter A/A* and must be large enough to ensure detection in the range desired so as to avoid a situation where smaller flaws cannot be discriminated, Fig. 11, without being so large as to cause premature saturation. It should also be noted that the increase in resolution (decreased standard error) for an increase in instrument sensitivity is not large compared to the penalties incurred when saturation is developed (Fig. 16).

Based on this work, it should be expected that each eddy current system will have its own characteristics and, therefore, limitations. Specifically, it is likely that the detection levels and saturation points will differ considerably from system to system. In addition to the problem of system to system variability, is the issue of probe response for a given system. Although they have not been treated herein, the variability of probe response, the effect of probe wear and the interaction of surface condition with signal response are additional inspection parameters which should be documented in order to increase the reliability of the system.

SECTION V

CONCLUSIONS

The observation of consistent relationships between eddy current signal characteristics and notch dimensions indicate that quantitative NDI for fatigue cracks is feasible.

Both the sensitivity level and the choice of a particular eddy current system are important variables to be considered when attempting to establish practical correlations between signal and flaw.

Using the semiautomated eddy current technique, small flaws in the size range of interest in this report could be readily detected. It is concluded, then, that from an NDI viewpoint RFC is a viable concept.

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